Study of neutrino oscillations in accelerator experiments

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QUARKS2010
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ν oscillations and mixing

3 families

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

atmospheric

solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \boxed{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix}} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

link between atmospheric and solar

***U* parameterization:** three mixing angles θ_{12} θ_{13} θ_{23}

CP violating phase δ

$$\Delta m_{ij}^2 = m_i^2 - m_j^2 \qquad \Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

two independent Δm^2

$$\Delta m_{12}^2 = \Delta m_{sol}^2 \approx 7.5\times10^{-5}\,\mathrm{eV}^2 \qquad \Delta m_{23}^2 \cong \Delta m_{31}^2 = \Delta m_{atm}^2 \approx 2.4\times10^{-3}\,eV^2$$

$\theta_{12} \sim 34^0$ $\theta_{23} \sim 45^0$ θ_{13} = ?

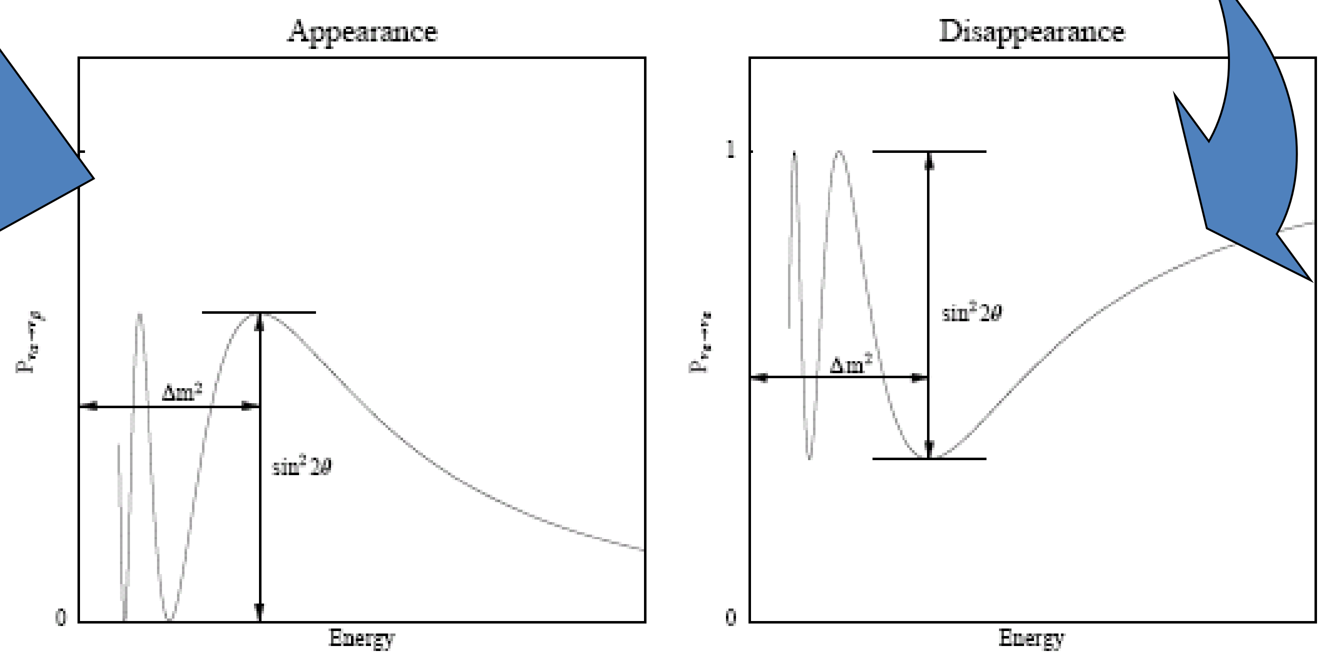
Oscillation experiments:
Appearance and Disappearance

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\Phi_{ij} \mp 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin 2\Phi_{ij}}$$

$$P_{\nu_\alpha\to\nu_\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right),$$

$$P_{\nu_\alpha\to\nu_\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$



Long baseline accelerator experiments

Main goals:

- **search for** $\nu_\mu \rightarrow \nu_e$ — θ_{13}
- **precise measurement** — Δm^2_{23} θ_{23}
- **mass hierarchy** — $\Delta m^2_{13} > 0$ **or** $\Delta m^2_{13} < 0$
- δ_{CP} — $\delta_{CP} \leftrightarrow \theta_{13}$ $U_{e3} = \sin\theta_{13} \exp(-i\delta_{CP})$

LBL experiments

cannot distinguish between Dirac and Majorana neutrinos

do not provide information about absolute ν mass

Neutrino oscillation experiments at accelerators

K2K (finished)
MINOS

$\nu_\mu \to \nu_\mu$ → Δm_{23}^2, $\sin^2 2\theta_{23}$

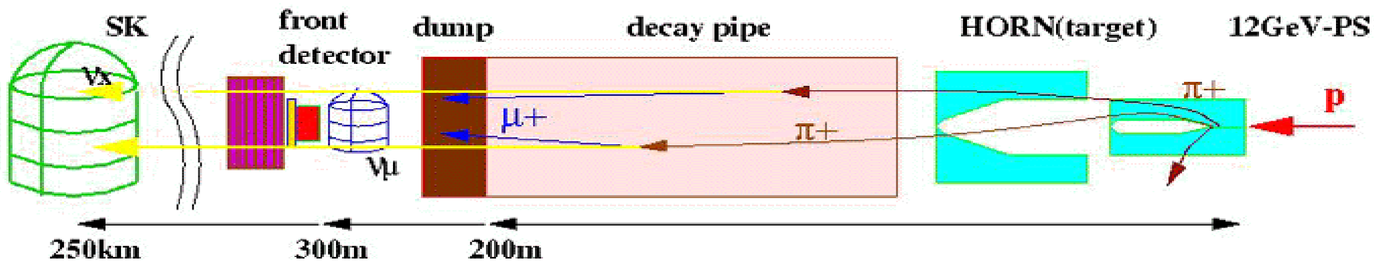
OPERA → $\nu_\mu \to \nu_\tau$

MiniBooNE → LSND → sterile ν

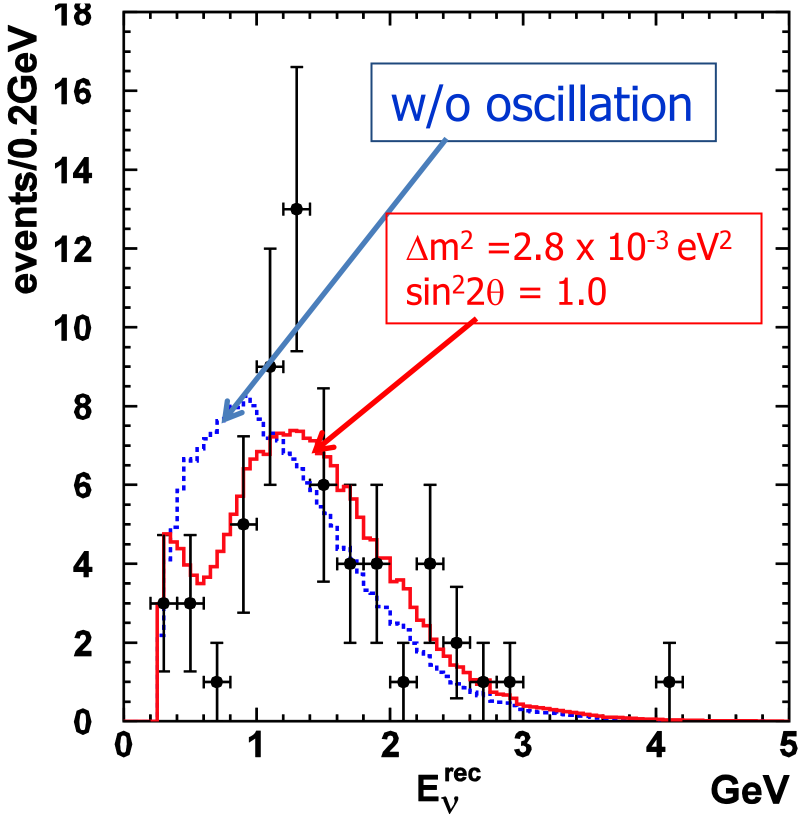
T2K
NOVA

$\nu_\mu \to \nu_e$ → θ_{13}, mass order, δ_{CP}(?)

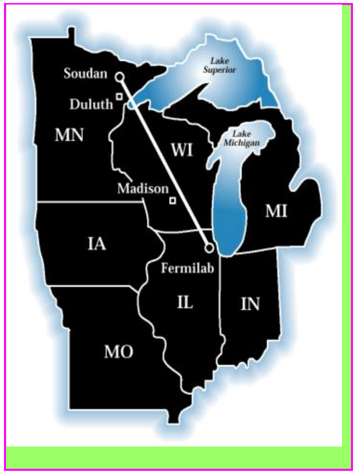
K2K: first LBL experiment

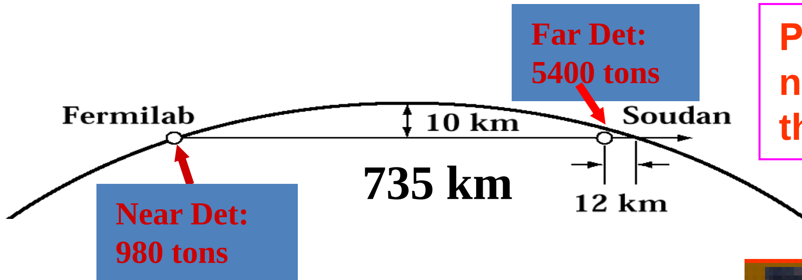


Confirmation of SK result:
oscillations of atmospheric neutrinos

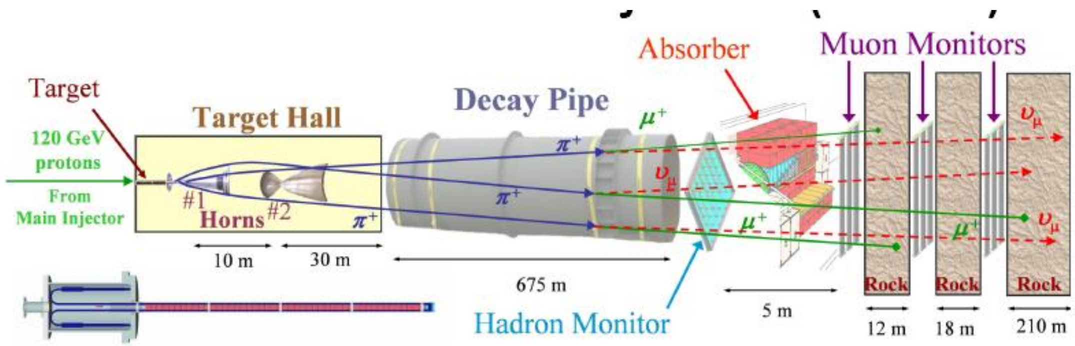


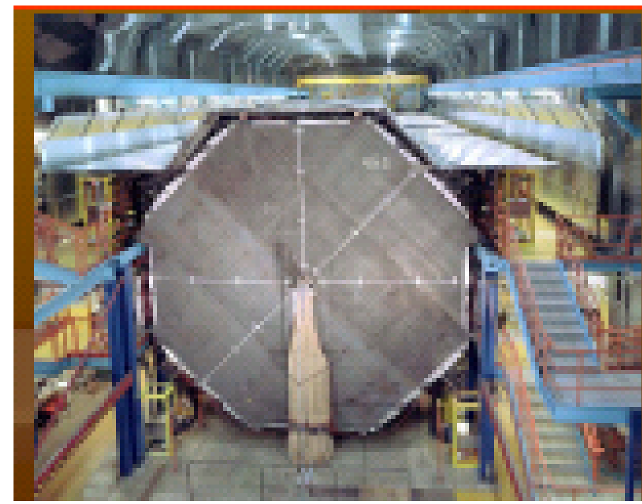
MINOS





Precise study of "atmospheric" neutrino oscillations, using the NUMI beam and two detectors





Proton beam: 120 GeV protons, 3×10^{13}POT/spill, 0.4 MW, 1 m segmented graphite target, 2 horns

ν- beam: ν_μ- 92.9%, anti-ν_μ- 5.8%, (ν_e + anti-ν_e)- 1.3%, peak energy ~(3-9) GeV

Detectors: ND, FD

Far Det: 5.4 kton magnetized Fe/Sci Tracker/Calorimeter at Soudan, MN (L=735 km)

Near Det: 980 ton version of FD, at FNAL (L ≈ 1 km)

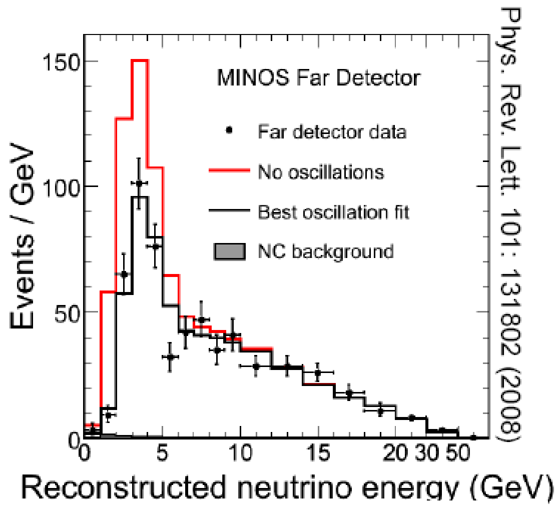
Data taking since 2006

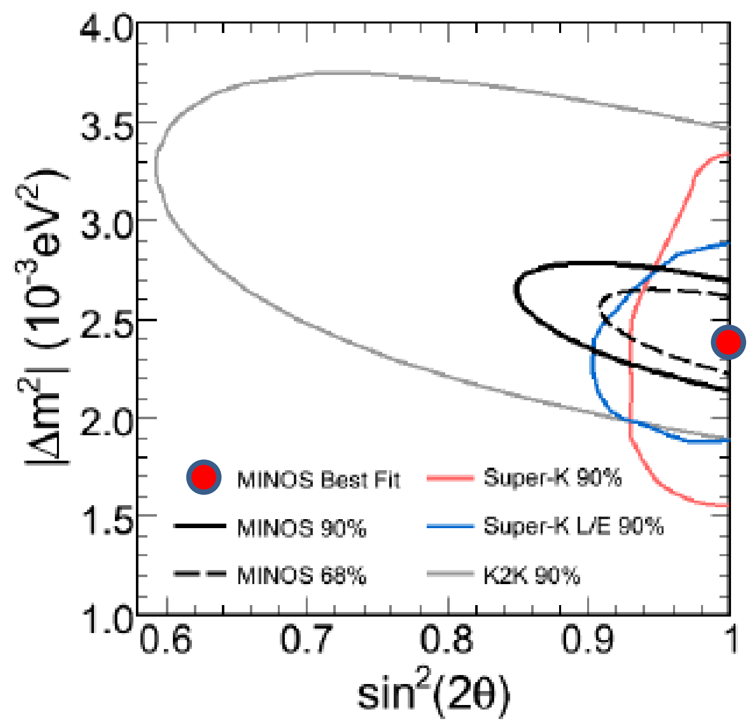
MINOS: $\nu_\mu \rightarrow \nu_\mu$

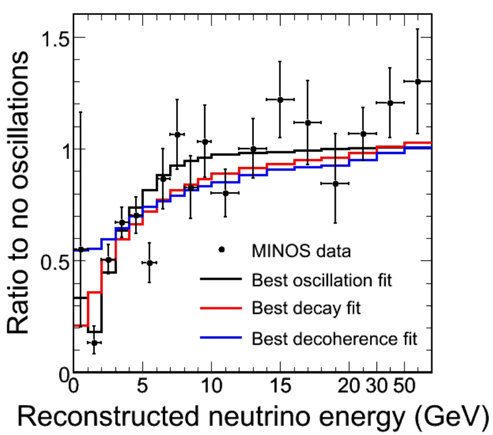
Phys.Rev.Lett. 101 131802 (2008)

3.36x10^{20} POT analyzed
Improved analysis

# expected	(no osc.)	1065±60
# observed		848







Δm^2_{23} =(2.43 ±0.13) x 10^{-3}
$\sin^2 2\theta_{23}$=1.00 -0.08

MINOS: $\nu_\mu \rightarrow \nu_e$

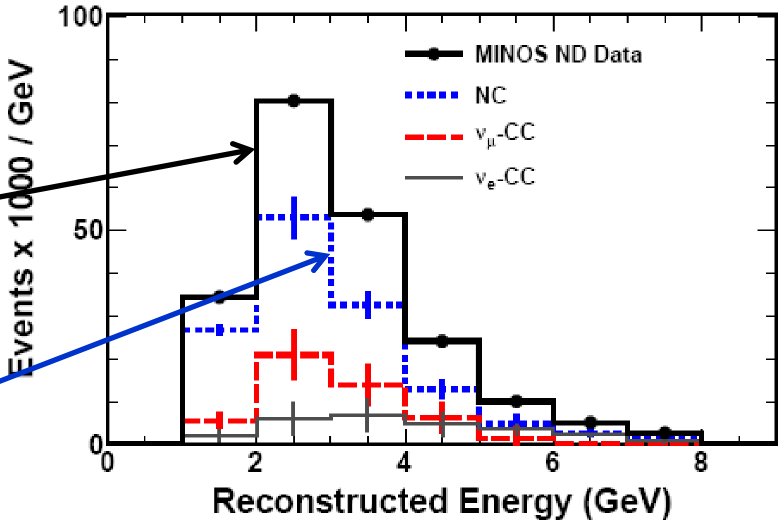
arXiv:1006.0996 [hep-ex]

For 3.18×10^{20} POT MINOS analysis suggested a hint for non-zero θ_{13}
(1.5 σ excess of ν_e in Far detector)
Detected 35 events
Expected bkg 27 $\pm$ 5 (stat) $\pm$ 2 (syst)

New result based on 7.01×10^{20} POT

Near Detector energy spectra of ν_e- CC event
(prior to possible oscillation)

NC – main source of background



MINOS: $\nu_\mu \rightarrow \nu_e$

7×10^{20} POT

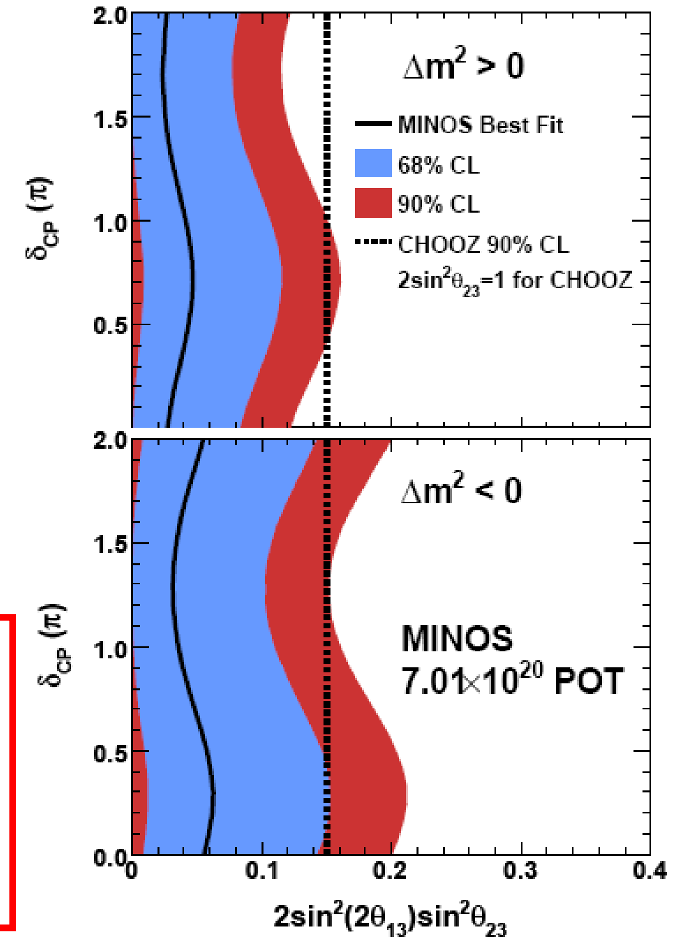
detected 54 ν_e events
expected bkg 49.1 ±7.0 (stat) ± 2.7 (syst)
(35.8 NC; 6.3 ν_μ- CC; 5.0 beam ν_e; 2.0 ν_τ)

Efficiency for selection of ν_e-CC events in Far Detector 41.6±1.0 %
Background suppression in Far Detector ~93%

for $\delta = 0$

$2\sin^2 2\theta_{13} \sin^2\theta_{23} < 0.12$ (90% c.l.) normal hierarchy

$2\sin^2 2\theta_{13} \sin^2\theta_{23} < 0.20$ (90% c.l.) inverted hierarchy



Best constraint on θ_{13} for almost all δ assuming $\Delta m^2 > 0$ and maximal $\sin^2\theta_{23}$

MINOS: $\nu_\mu \rightarrow \nu_s$

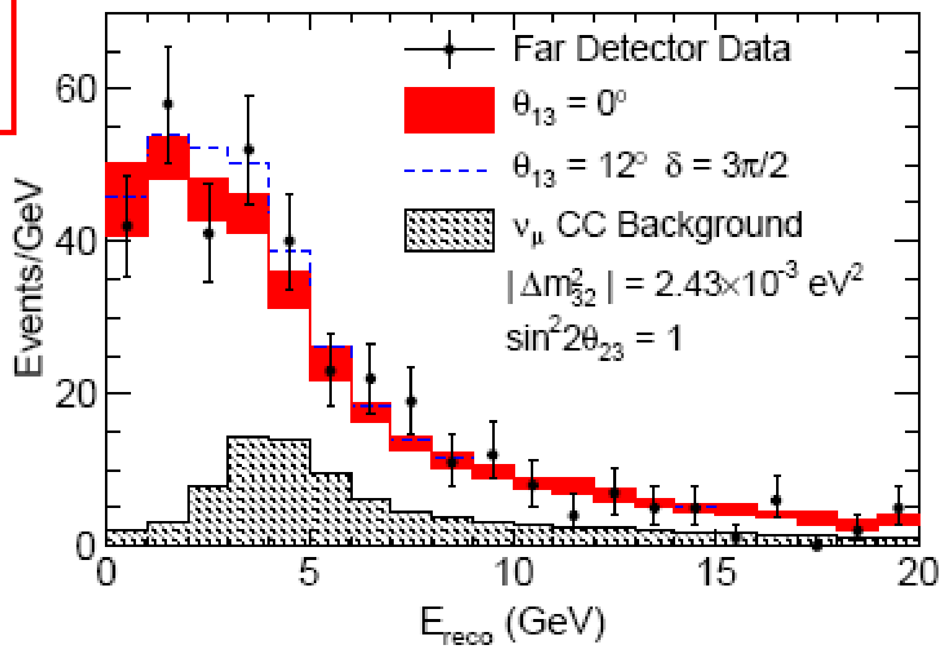
Phys.Rev.D81:052004 (2010), arXiv:1001.0336

deficit of NC events at Far Detector would be an indication of existence of sterile neutrinos

3.2×10^{20} POT, peak neutrino energy 3.3 GeV

388 NC events detected in Far Detector
377 $\pm$ 19.4(stat) $\pm$18.5(syst) expected
from standard 3-flavor neutrino models

R =1.04 $\pm$ 0.08(stat) $\pm$ 0.07(syst) – 0.1(ν_e)



For maximally allowed ν_e appearance

$$f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} < 0.55 \text{ (90\% CL)}$$

OPERA

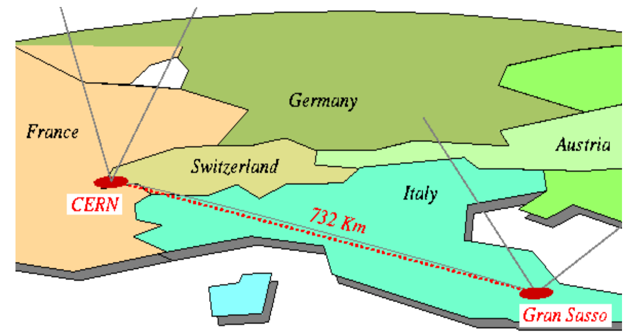
C. Sirignano, talk at this conference

$\nu_\mu \to \nu_\tau$ direct search

$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2\theta_{23}\sin^2[1.27\Delta m^2_{23}L(\text{km})/E(\text{GeV})\,]$

High energy, long baseline ν beam

($E \approx 17$ GeV $L \sim 730$ km)

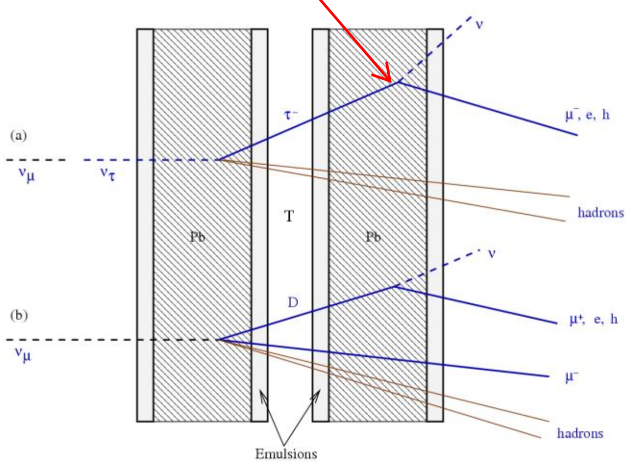


kink

Target mass ~1300t

$E/L \sim 2.3\times10^{-2} \sim 10\Delta m^2_{23}$ (atm)

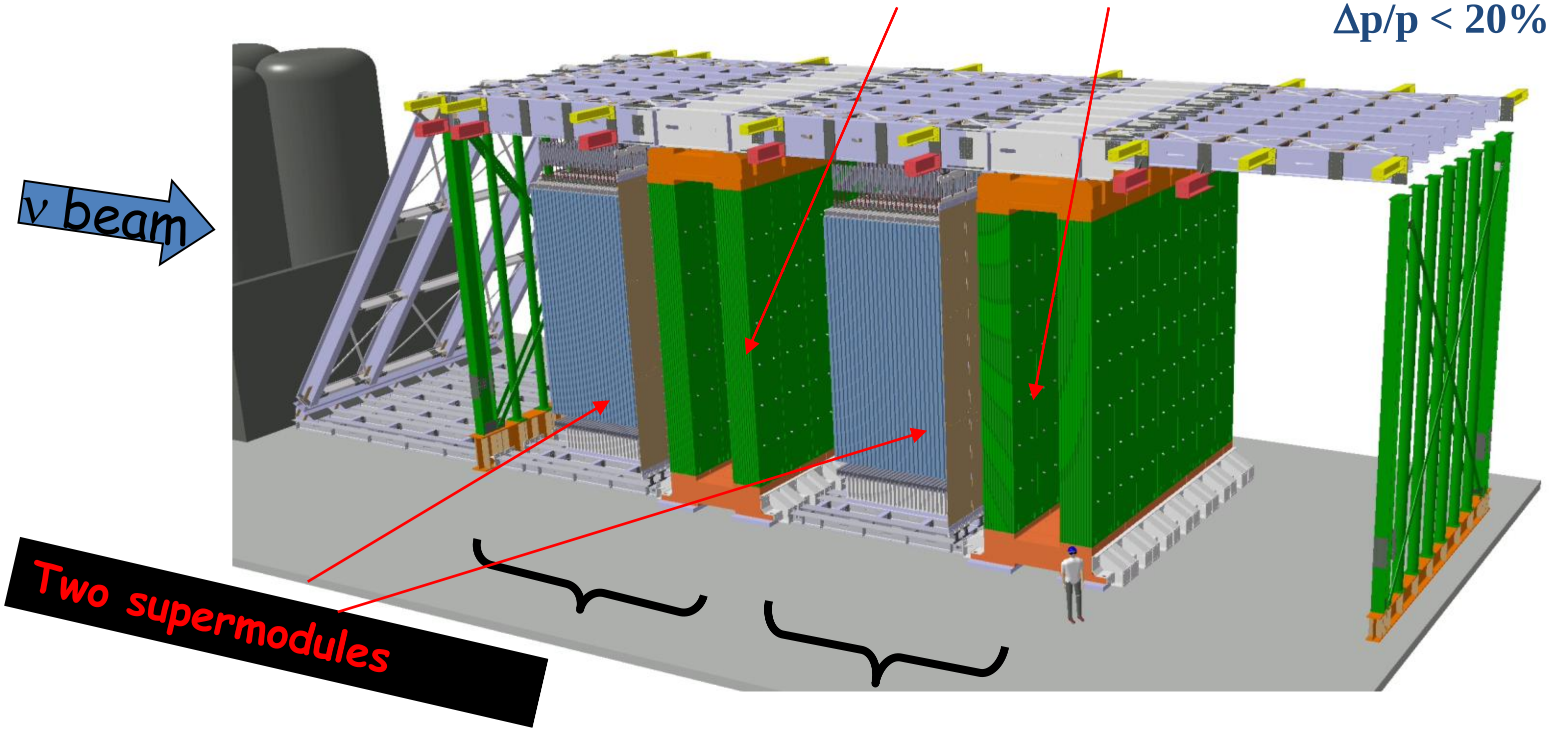
pure beam: 2% anti ν_μ <1% ν_e



Main background

Expectation after 5 years data taking:
~22000 ν interactions
~120 ν_τ interactions
~10 ν_τ reconstructed
<1 background event

OPERA Detector



$\varepsilon^{miss}_{charge} \approx (0.1 \div 0.3)\%$

$\Delta p/p < 20\%$ for $p<50$ GeV

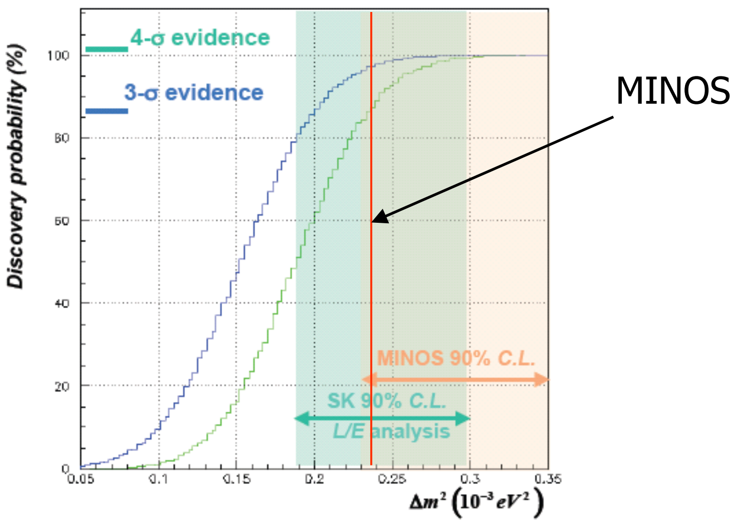
Hybrid Detector:
- Two supermodules – Target Mass ~1.8 ktons
- 2 Magnetic spectrometers with RPC & Drift tubes
- 2 x [31 Target Tracker planes and Target Walls]
- ~200000 "ECC bricks" (56 Pb/Emulsion layers)
- 12 M Emulsion plates (thin double-coated)

OPERA: $\nu_\mu \to \nu_\tau$ sensitivity

full mixing,
5 years run
4.5×10^{19} pot/y

expected

τ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Background
$\tau \to \mu$	17.7	2.9	0.17
$\tau \to e$	17.8	3.5	0.17
$\tau \to h$	49.5	3.1	0.24
$\tau \to 3h$	15.0	0.9	0.17
Total		10.4	0.75



Data taking since 2007
Accumulated in 2008-09 ~5.3×10^{19} POT
Analysis of data with 1.89×10^{19} POT

2010: 1st ν_τ candidate event is observed

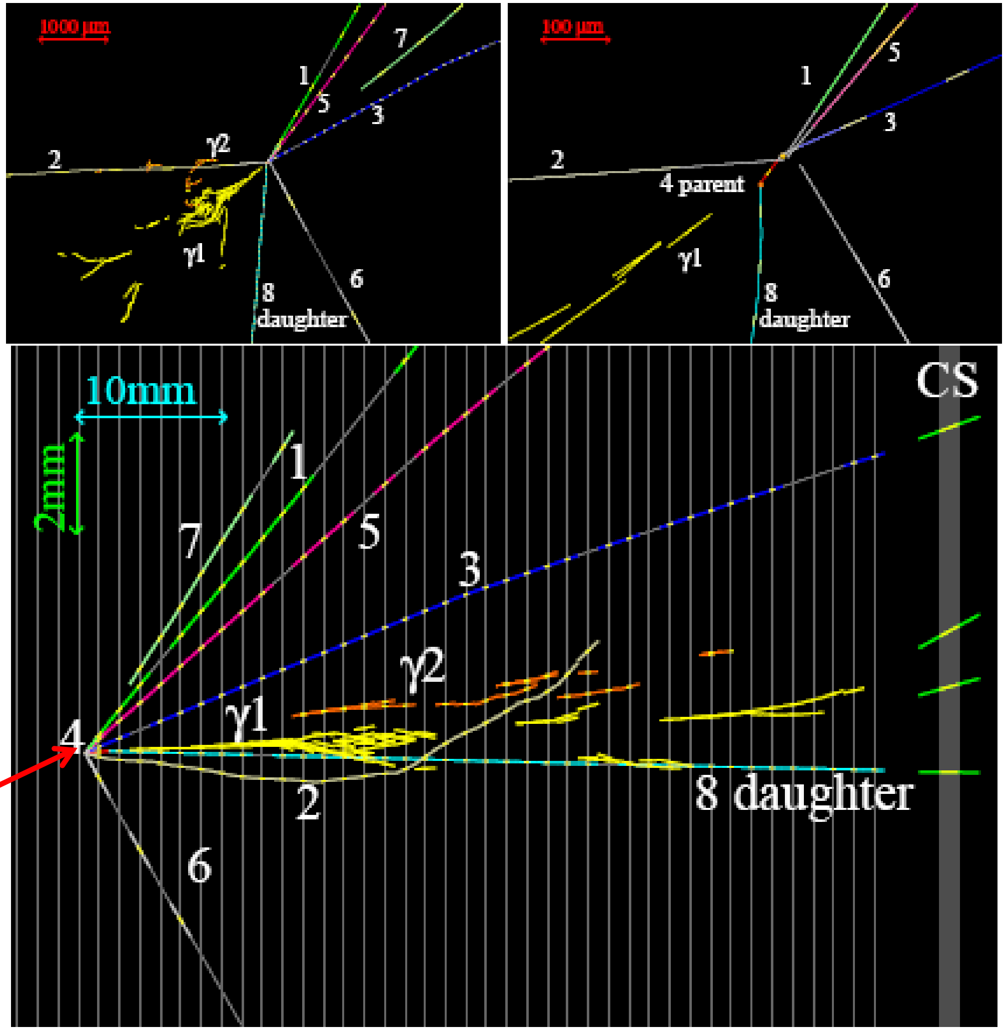
OPERA: first ν_τ candidate

arXiv:1006.1623 [hep-ex]

decay
$\tau^- \rightarrow h^-(n\pi^0)\nu_\tau$

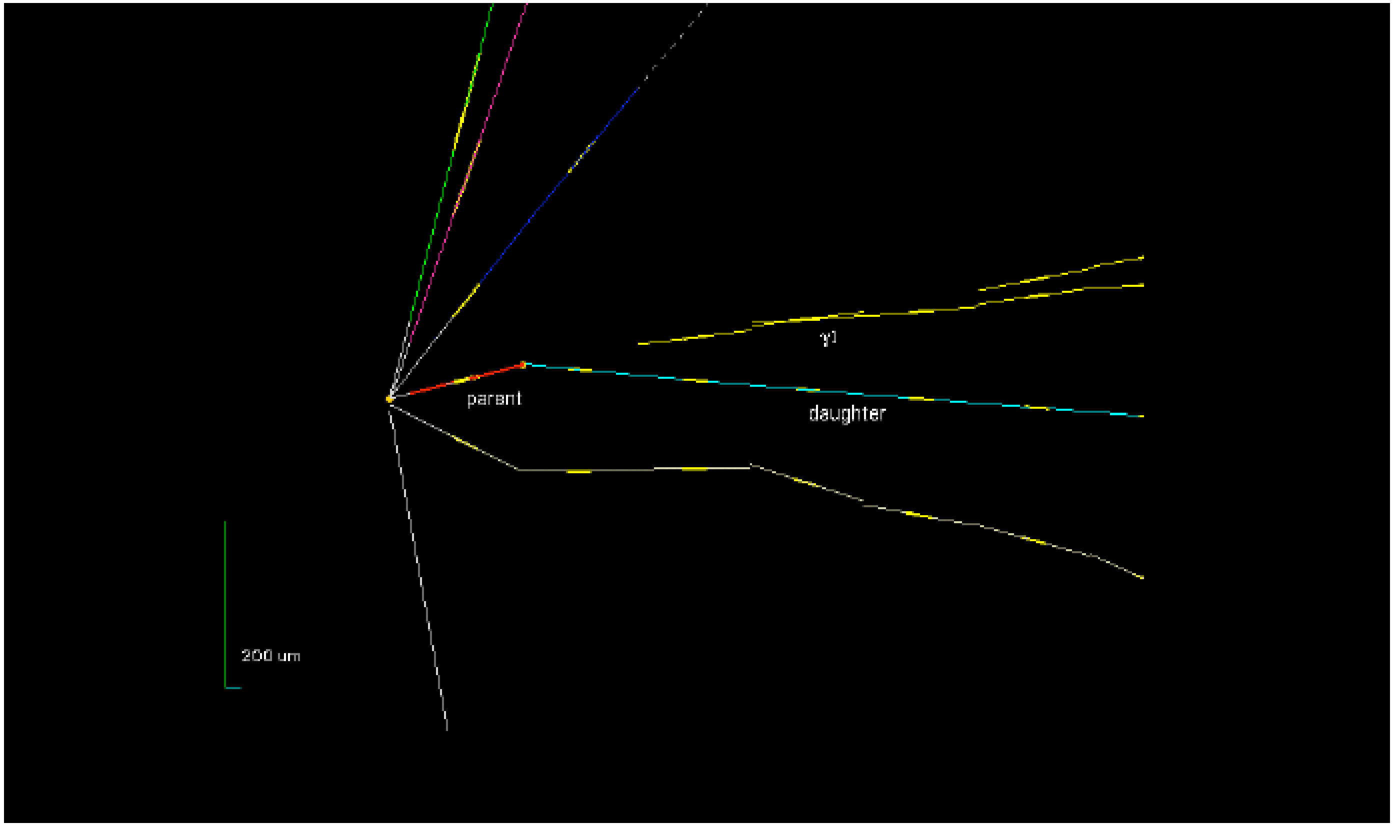
- Expected number of ν_τ events
  0.54 ± 013 (syst)
- Probability that this event due
  to background fluctuation 4.5%
- Significance of observation 2.01σ

- 20 charm decays observed
- expectation from MC 16.0 ± 2.9



ν_τ interaction
point

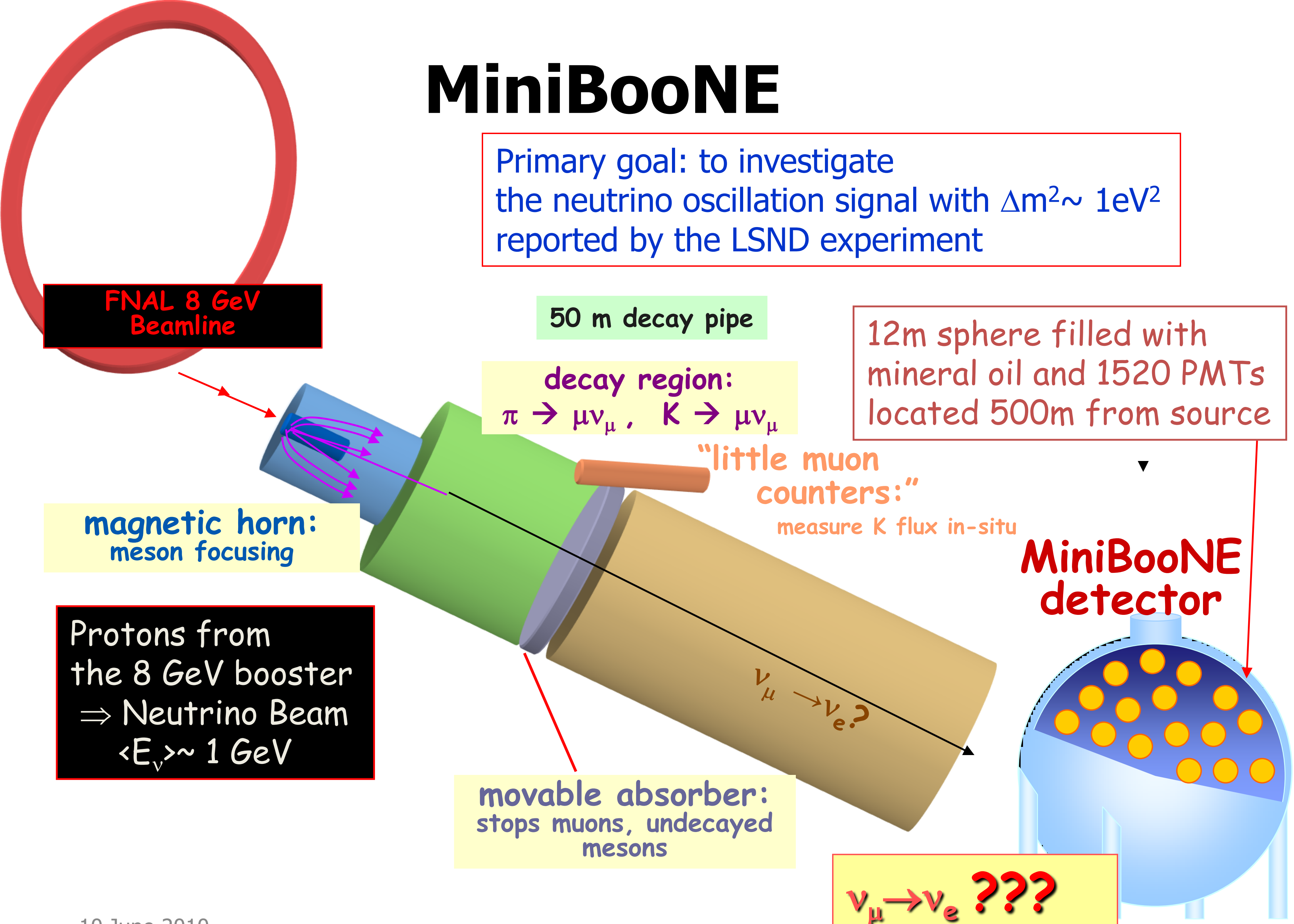
A milestone in neutrino physics



Congratulations to OPERA!

MiniBooNE

Primary goal: to investigate
the neutrino oscillation signal with $\Delta m^2 \sim 1 eV^2$
reported by the LSND experiment

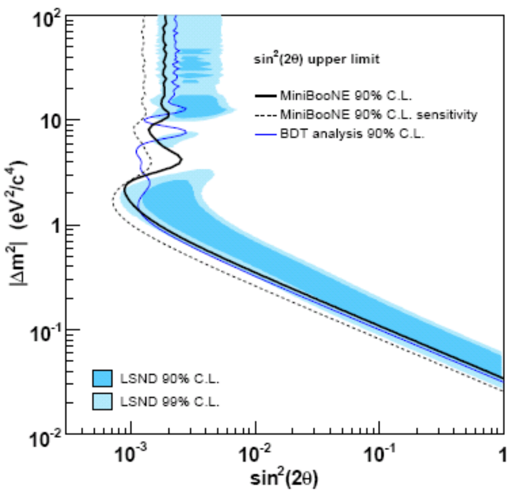


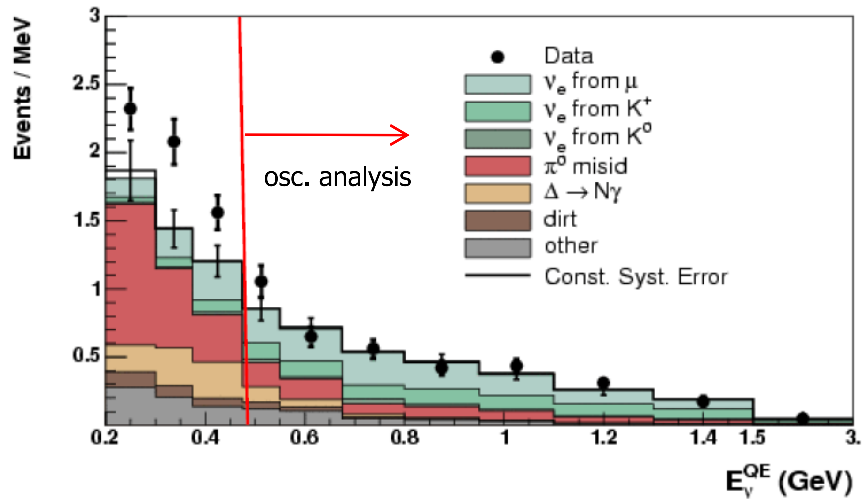
MiniBooNE $\nu_\mu \rightarrow \nu_e$

PRL 98:231801, 2007
PRL 102:101802,2009

6.46 x 10^{20} POT

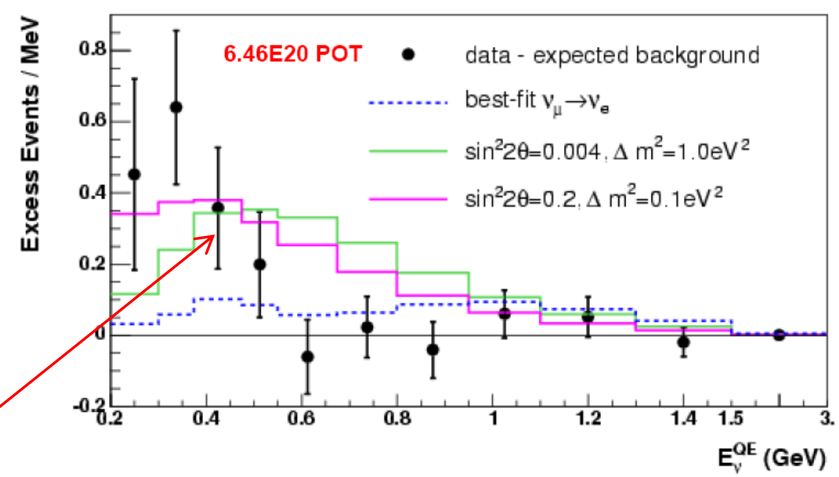
No ν_e excess in oscillation signal region E_ν> 475 MeV





however

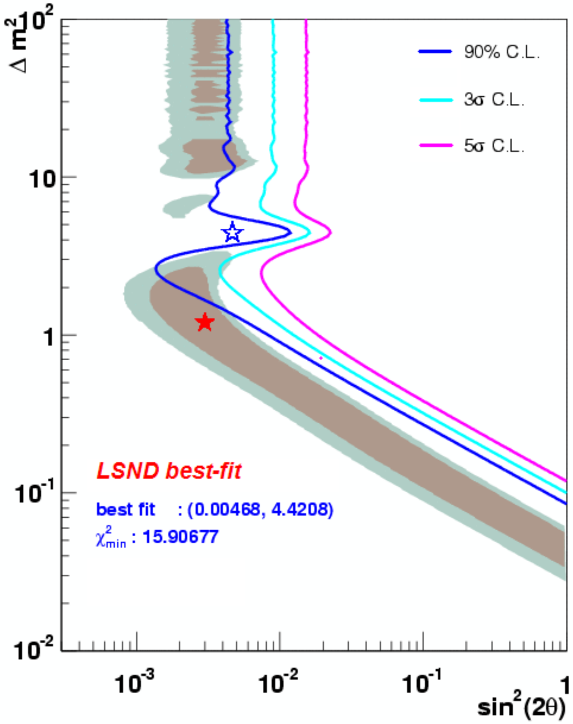
Excess 128.8 ± 20.4 ± 38.3 events above background for 200-475 MeV



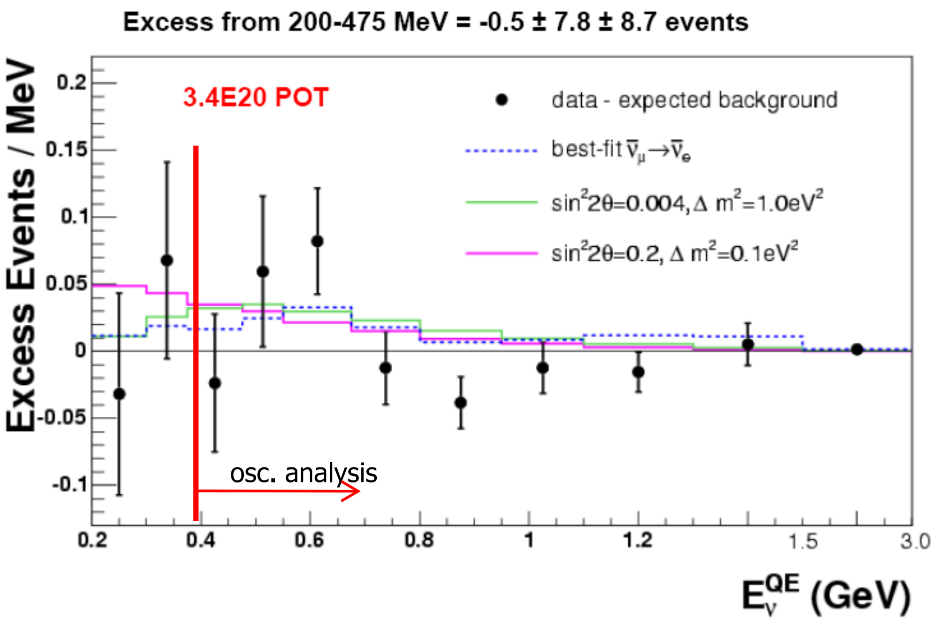
Background-subtracted

MiniBooNE anti-$\nu_\mu \rightarrow$ anti-ν_e

W.C. Louis, Aspen 2010



PRL 103, 111801 (2009)



anti-ν_e data are inconclusive (low statistics) but consistent with LSND
anti-ν_e result with 6×10^{20} POT is expected soon, with $\sim10^{21}$ POT in 2011

Possible interpretations

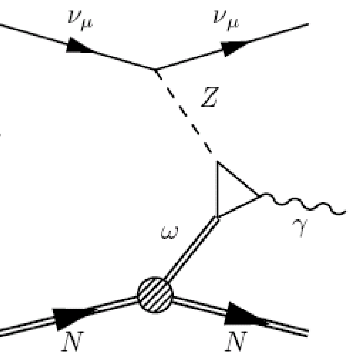
if low-energy excess for ν_μ is confirmed to be a real signal

- Non-oscillation

  $\nu + N \rightarrow \nu + N + \gamma$

Coupling between γ, Z and ω

$\sigma \sim 2.6\times10^{-41}(E_\nu/\mathrm{GeV})^6(g_\omega/10)^4\ \mathrm{cm}^2$



С.С.Герштейн, Ю.Я.Комаченко, М.Ю.Хлопов, ЯФ 33 (1981) 1597
J.Harvey, C.Hill, R.Hill, arXiv:0708.1281
R.Hill, arXiv:0905.0291; Jenkins,Goldman, arXiv:0906.0984

- Oscillation

  3 +1 model
  M.Maltoni, T.Schwetz, arXiv:0051.0107

  3 + 2 or 3 + 3 models
  M.Maltoni, T.Schwetz, arXiv:0051.0107
  A.Nelson, J.Walsh, arXiv:0711.1363

  Extra dimensions
  H.Pas, S.Pakvasa, T.Weiler, hep-ph/0504096 (predicted low-energy excess)

Lorentz violation
T.Katori, A.Kostelecky, R.Tayloe, hep-ph/0606154

Heavy Sterile Neutrino Decay
S.Gninenko, arXiv:0902.3802

VSBL Electron Neutrino Disappearance
C.Giunti, M.Laveder, arXiv: 0902:1992

Second generation LBL experiments

Off Axis Neutrino Beams

- Increase flux on oscillation maximum
- Reduce high-energy tail and NC backgrounds
- Reduce ν_e contamination from K and μ decay

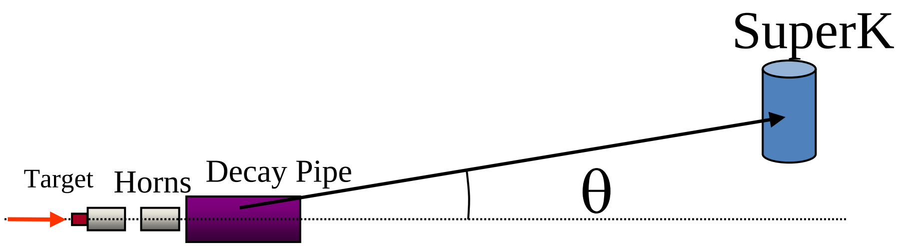
↓

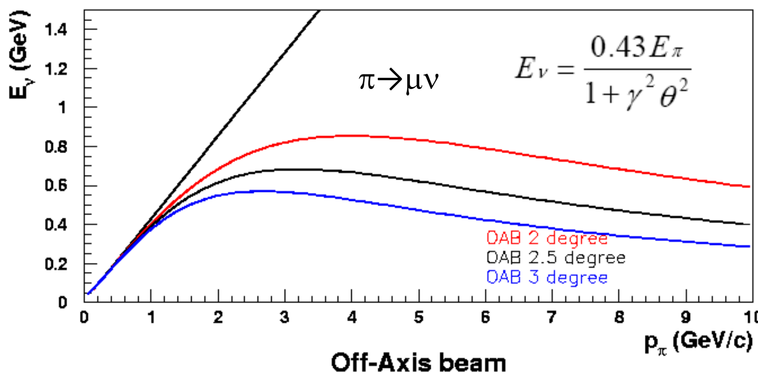
T2K

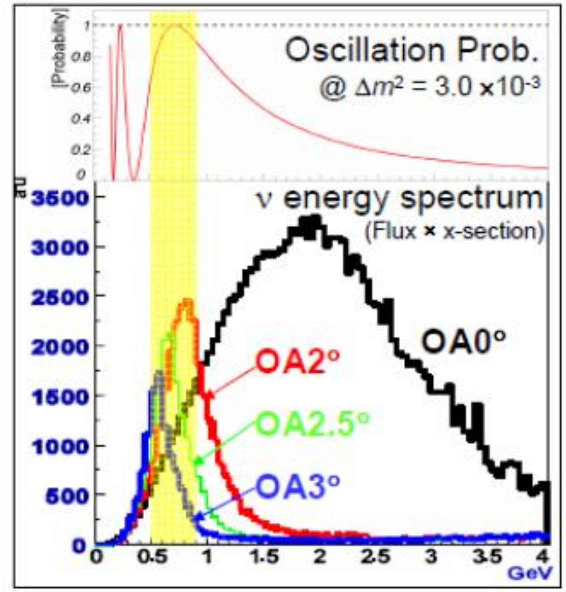
NOVA

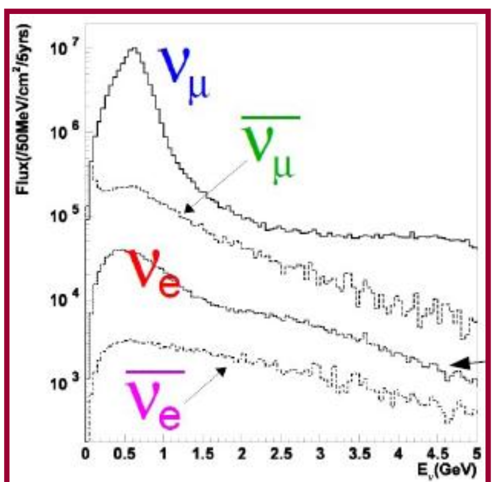

T2K
Main goals:
J.Kameda, talk at this conference
ν_e appearance (θ_{13})
CP phase δ (degrees)
$\Delta m^2_{13} = 2.5\times10^{-3}$ eV^2
$\Delta m^2_{13} = 1.9\times10^{-3}$ eV^2
$\Delta m^2_{13} = 3.0\times10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1$
$\Delta m^2_{12} = 8.2\times10^{-5}$ eV^2
$\tan^2\theta_{12} = 0.4$
> x10
CHOOZ excluded
$\sin^2 2\theta_{13}$
Precise measurement
$\delta(\Delta m^2_{23})$ ~ 1×10^{-4}eV^2
$\delta(\sin^2 2\theta_{23})$ ~ 0.01
Current Experimental limits
Δm^2 (10^{-3} eV^2)
MINOS Best Fit
MINOS 90%
MINOS 68%
Super-K 90%
Super-K L/E 90%
K2K 90%
750kWx5yr Operation
(~8×10^{21}POT)
Assuming $\sin^2 2\theta_{23}$=1.0,
Δm^2_{23}=2.4×10^{-3}eV^2
99%
90%
68%
w/o syst. errors
SuperKamiokande
Super-K
295km
J-PARC
KEK
Kanazawa
Gifu
Nagano
Japan
Kofu
Maebashi
Saitama
Funabashi
Mito
Chiba
Niigata
Honshu
Fukushima
Sado
E135°
E137°
E139°
E141°
N37°
Nuclear and Particle Physics Experimental Hall
Materials and Science Facility
3GeV Synchrotron
Neutrino Facility
50GeV Synchrotron
Linac
Accelerator-Driven Transmutation Experimental Facility
Image NASA
© 2007 Europa Technologies
Image © 2007 TerraMetrics
© 2007 ZENRIN
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

T2K off-axis beam



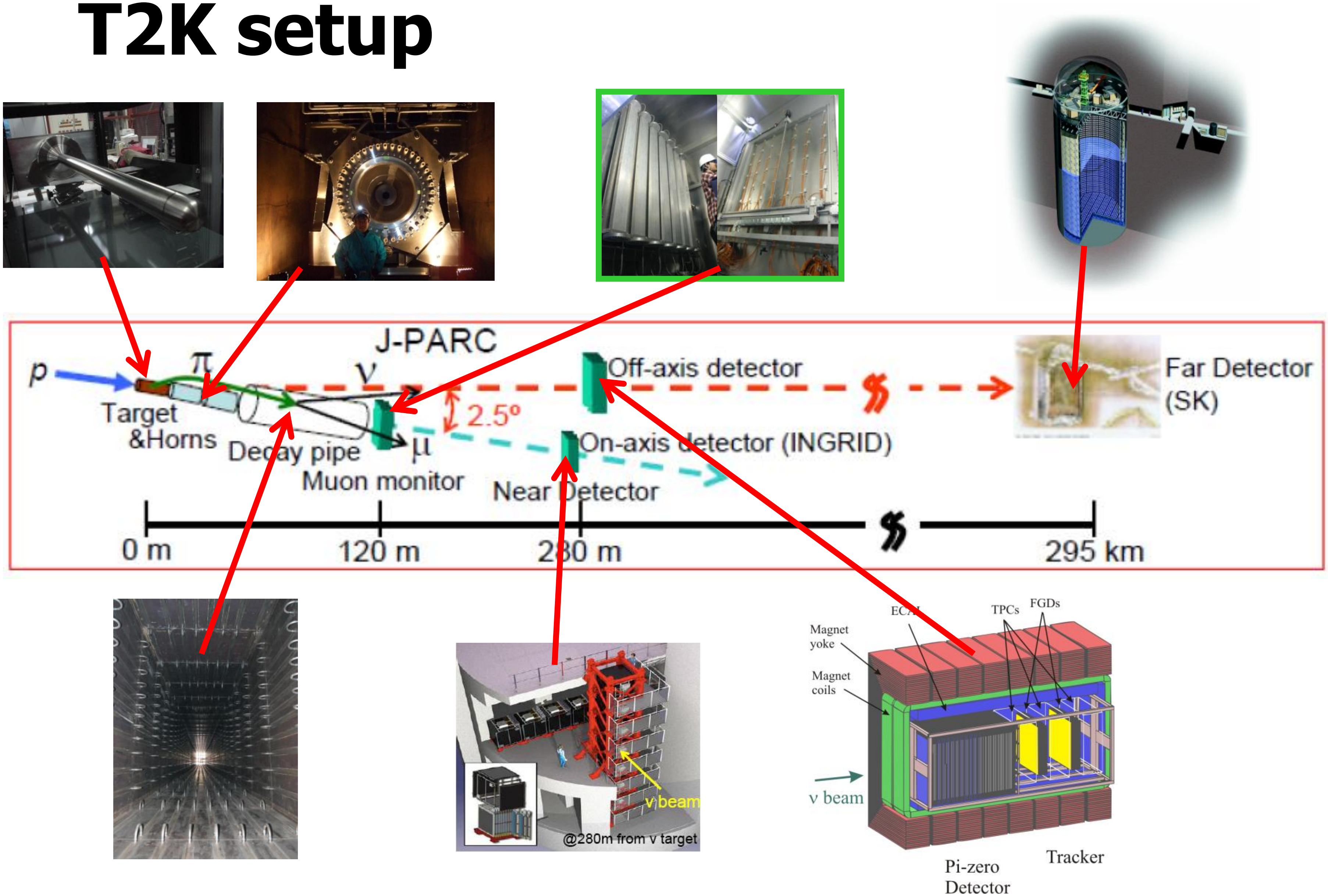






T2K:
Quasi-monochromatic ν_μ (95%) beam
~0.4% ν_e at peak energy ~700 MeV

T2K setup

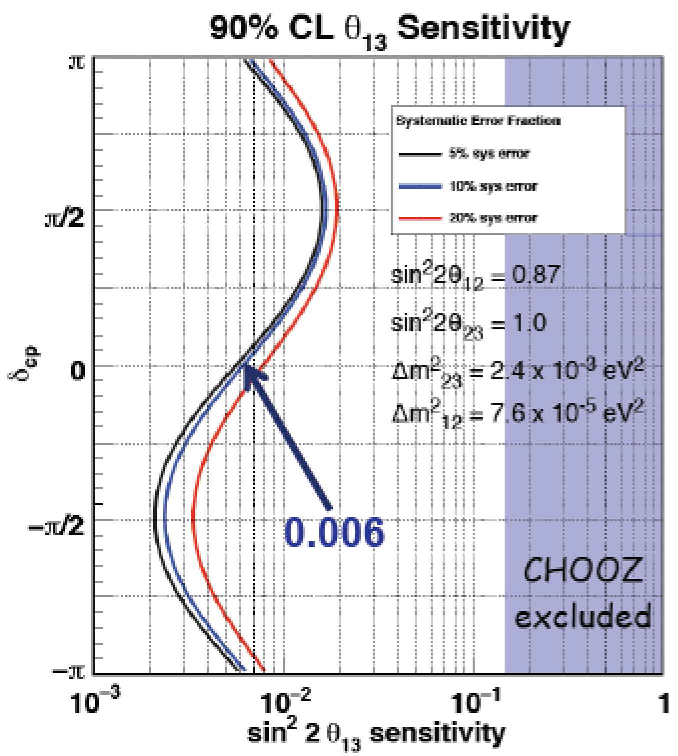

J-PARC
p
π
ν
μ
Target
&Horns
Decay pipe
Muon monitor
2.5°
Off-axis detector
On-axis detector (INGRID)
Near Detector
Far Detector
(SK)
0 m
120 m
280 m
295 km
ν beam
@280m from ν target
Magnet yoke
Magnet coils
ECAL
TPCs
FGDs
ν beam
Pi-zero Detector
Tracker

T2K physics goals

Proton energy 30 GeV, integral 8 x 10^{21} POT (~5 years)

ν_e appearance

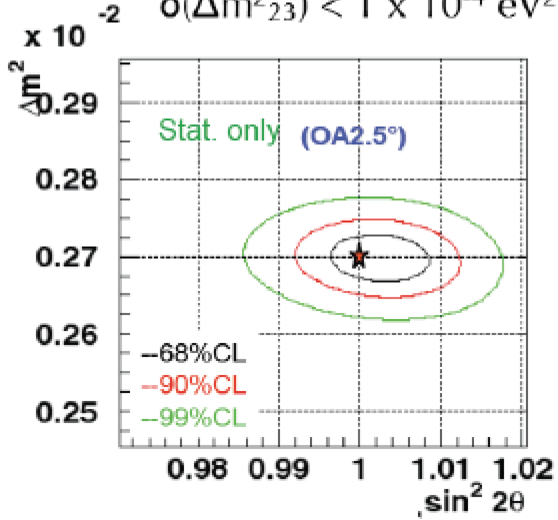
> x10 improvement from CHOOZ limit



ν_μ disappearance

$\delta(\sin^2 2\theta_{23}) \sim 1\%$

$\delta(\Delta m^2_{23}) < 1 \times 10^{-4}$ eV^2

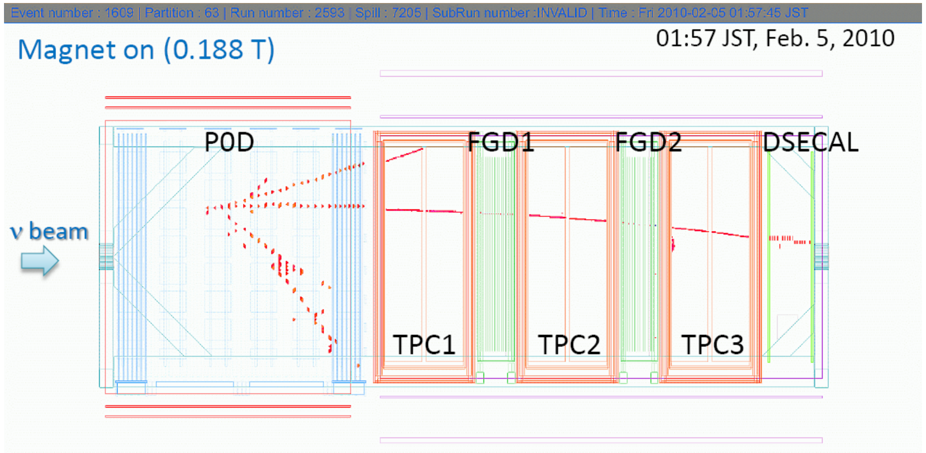


@ 8 x 10^{21} protons(30GeV) on target

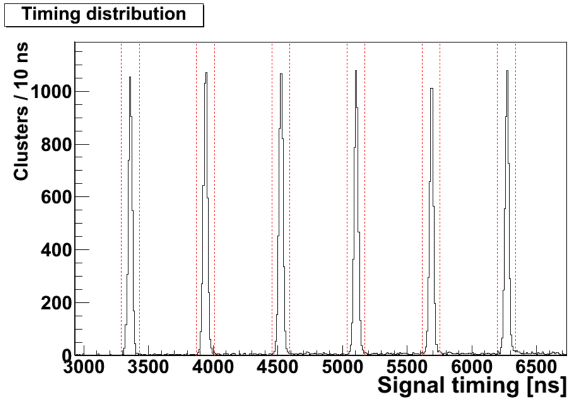
Status of T2K

Construction completed	**March 2009**
Physics run started	**January 2010**
First SuperK event	**February 2010**

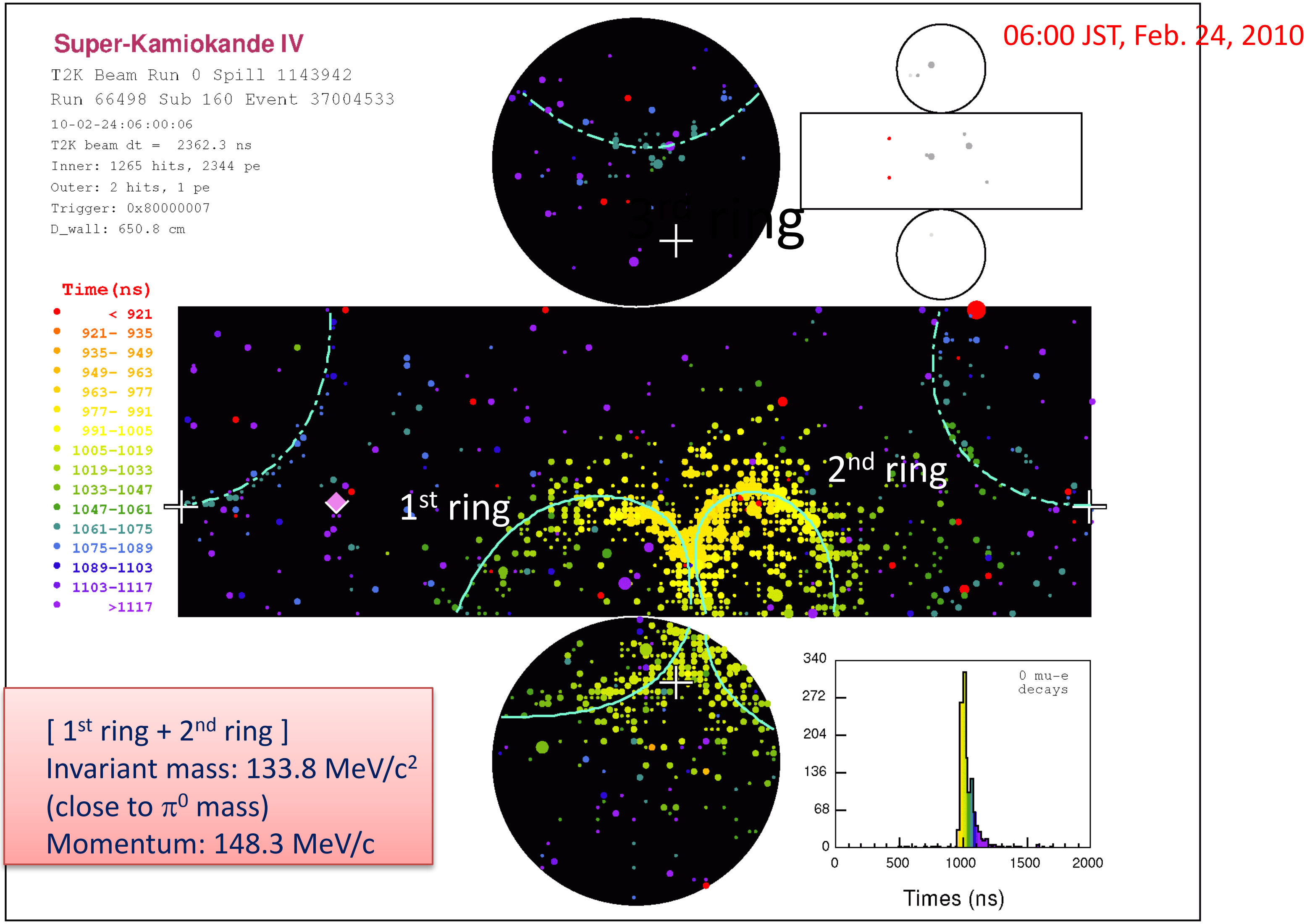
ν event in ND280



Timing of ν events in FGD



T2K: 1st neutrino event in SK



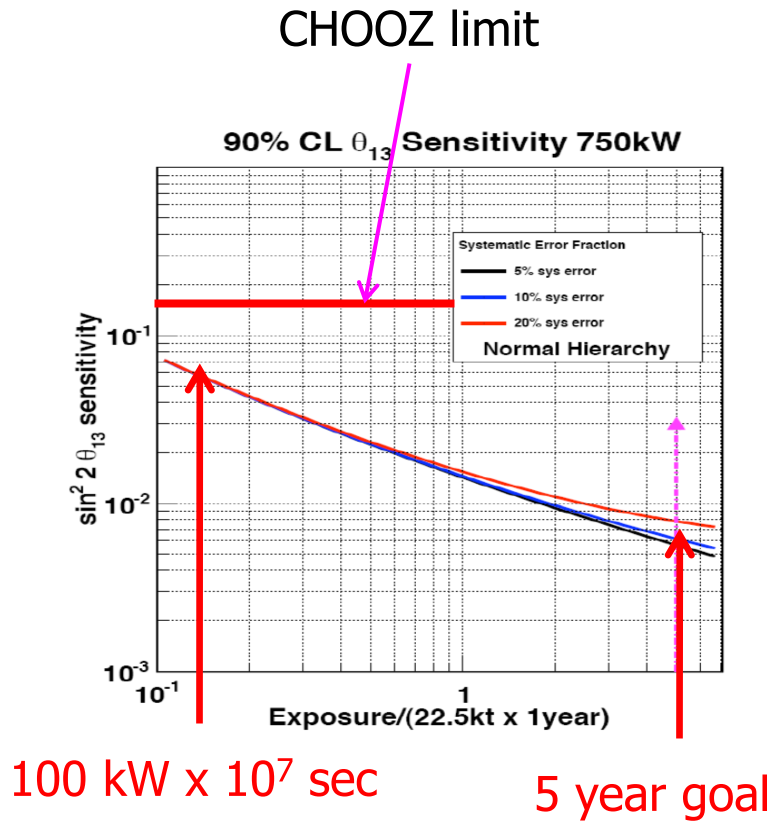
[1st ring + 2nd ring]
Invariant mass: 133.8 MeV/c^2
(close to π^0 mass)
Momentum: 148.3 MeV/c

T2K Outlook & 2010 goals

- First physics run till July 2010
  beam power ~50kW

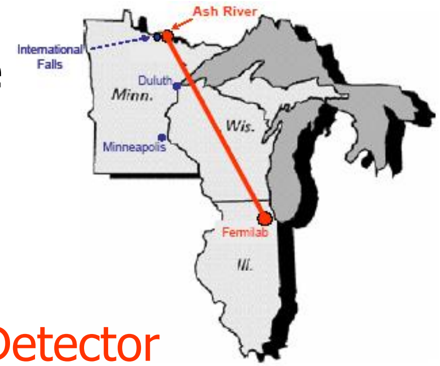
- Upgrade of kicker magnets and horn power supply; remaining Ecal installation and commissioning
  July – October, 2010

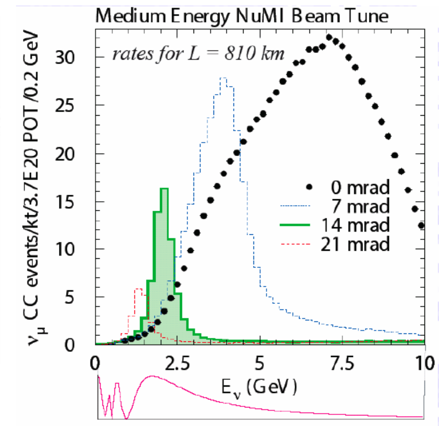
- Second physics run start in November 2010
  beam power $\geq$ 100kW

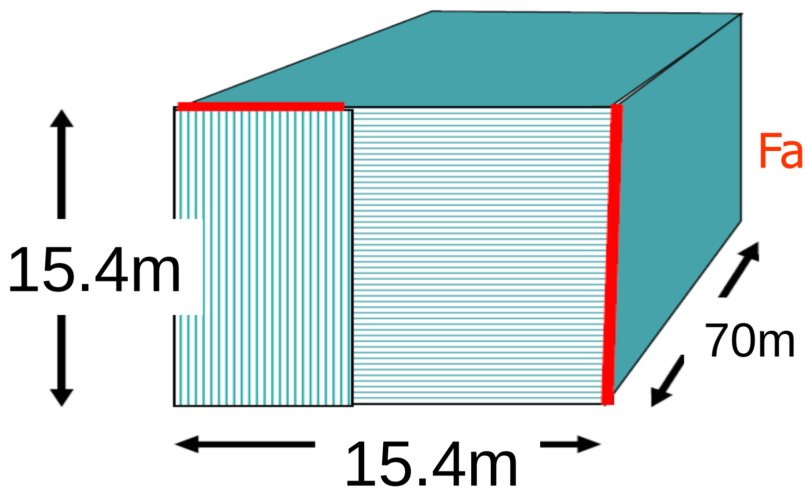


NOvA

810 km baseline







Far Detector

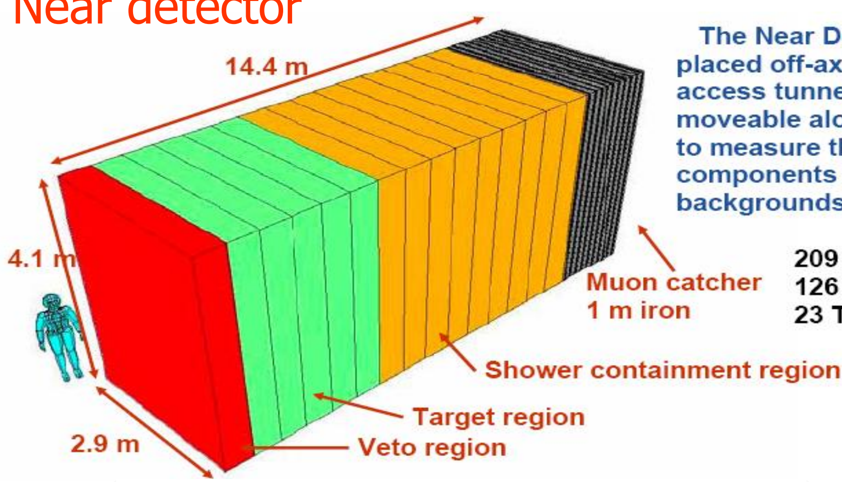
15 ktons 15.4m x 15.4m x 70m

1003 liquid scintillator planes (~80% active)

Scintillator cells 3.8 x 6.0 x 1540 cm^3

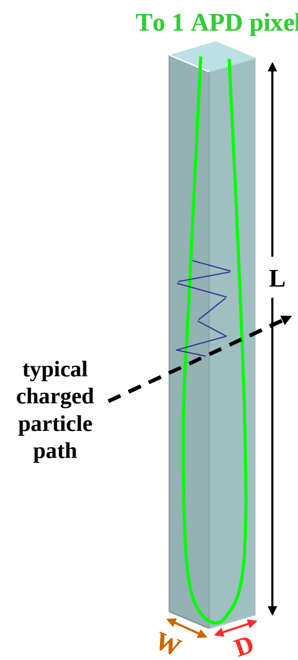
Read out from one side per plane with APDs

Near detector



The Near Detector will be placed off-axis in the MINOS access tunnel and will be moveable along the tunnel to measure the different components of the backgrounds.

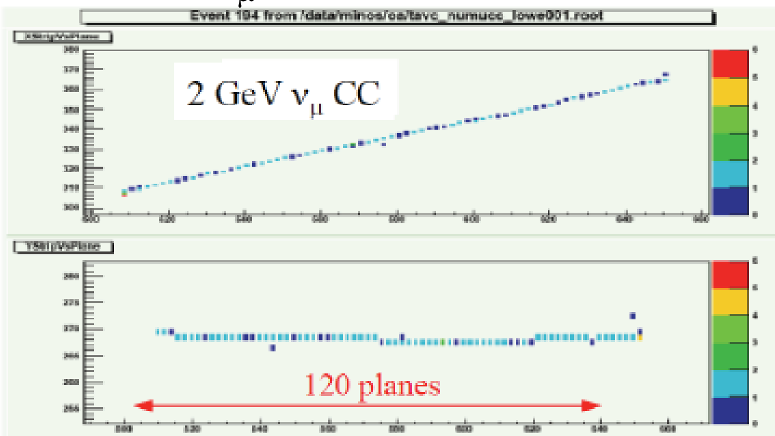
209 T
126 T totally active
23 T fiducial



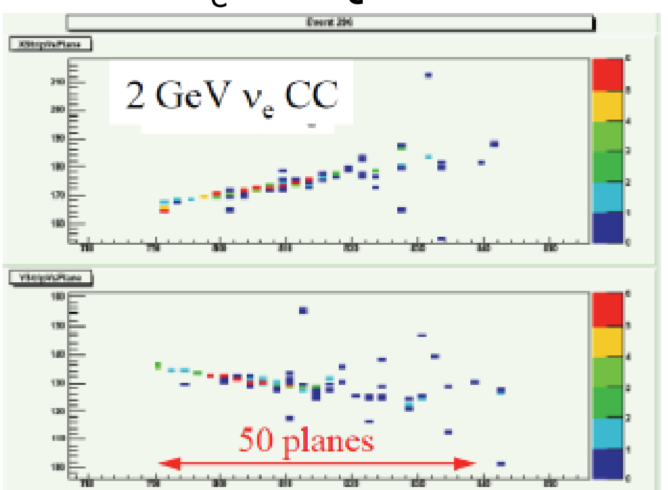
Active element:
Liquid scintillator
U-shaped WLS fiber

NOνA event patterns

ν_μ CC Quasi-elastic

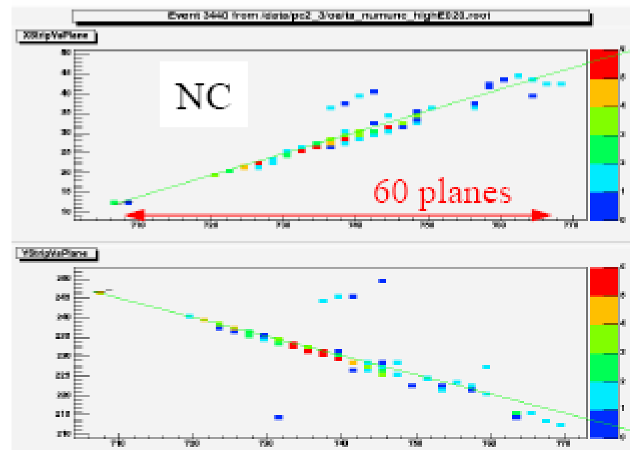


ν_e CC Quasi-elastic



Neutral current

$\nu_\mu \mathbf{N} \to \nu_\mu \mathbf{p}\, \pi^o$



$\nu_\mu \mathbf{N} \to \nu_\mu \mathbf{p}\, \pi^o$

E_ν = 10.6 GeV

E_p = 1.04GeV

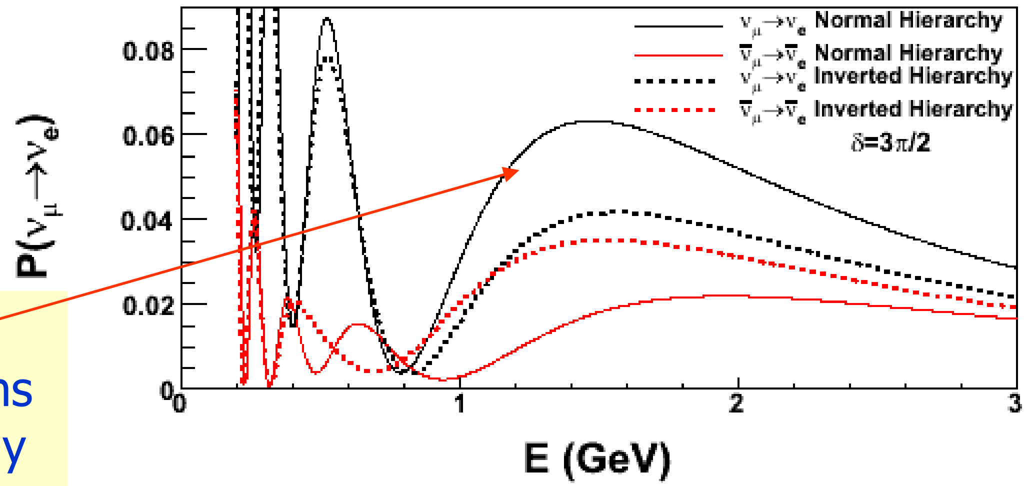
$E_{\pi o}$ = 1.97GeV

Good particle identification and selection of ν_e events

NOνA

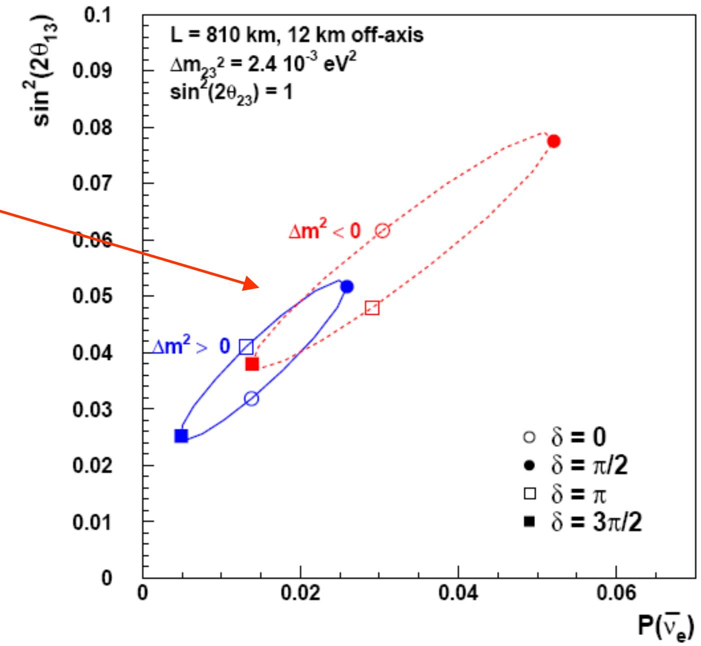
P($\nu_\mu \rightarrow \nu_e$) depends on
$\sin^2 2\theta_{13}$ sign Δm^2_{23} δ_{CP}

matter effects
increase (decrease) oscillations
for normal (inverted) hierarchy
for ν



Mass hierarchy can be resolved if θ_{13} near to present limit using both ν anti-ν beams and $\sin^2 2\theta_{13}$ from T2K + reactor experiments

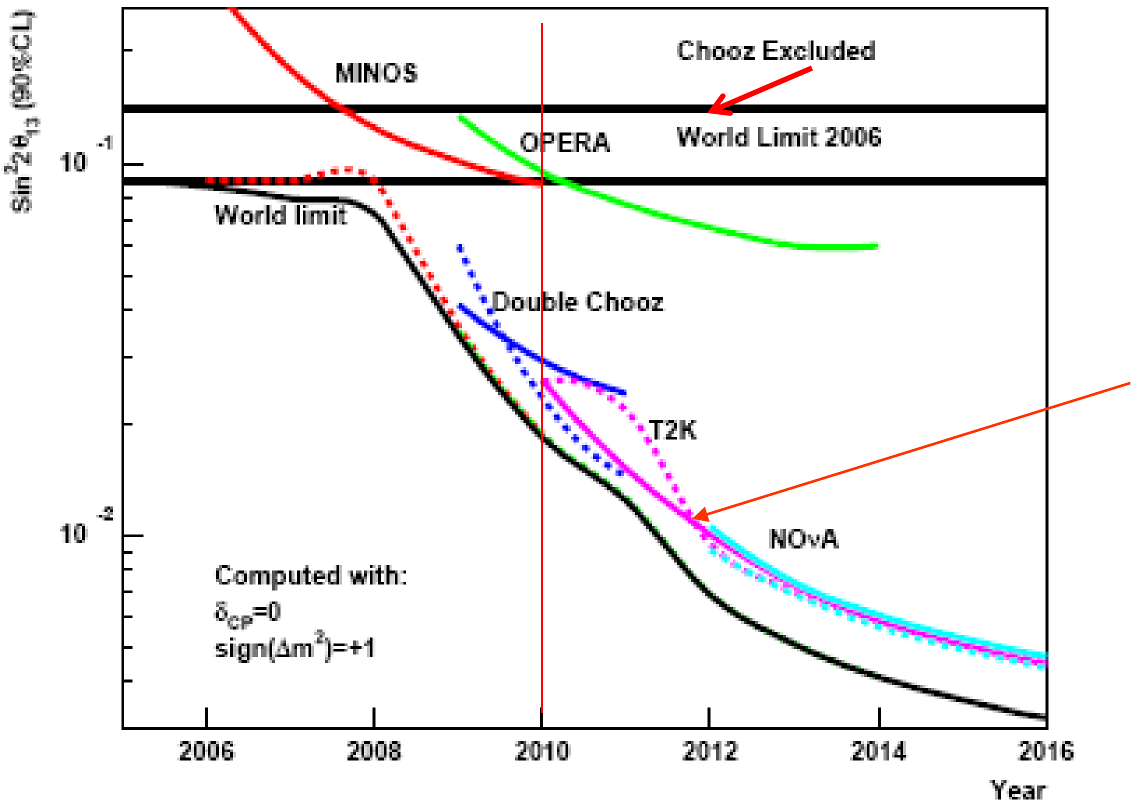
$\sin^2(2\theta_{13})$ vs. P($\bar{\nu}_e$) for P(ν_e) = 0.02



Full construction started 2009
Far detector construction 2011-13

θ_{13} sensitivities vs time

as expected in 2006



A.Blondel et al., hep-ph/0606111

Short baseline reactor experiments
Double-Chooz and Daya Bay $\longrightarrow$ **θ_{13} (insensitive to δ_{CP})**

Conclusion

- **Neutrino oscillations – physics beyond the Standard Model**

- Accelerator experiments: very productive and provide exiting results

- **MINOS, OPERA, MiniBooNe** successfully taking data

- **T2K** running for physics since January 2010

- Main goal for LBL accelerator experiments: θ_{13} – key parameters which determines the future of these experiments

- Non-zero θ_{13} will give us a chance to measure mass hierarchy and to probe CP violation in lepton sector

New results are coming next week!